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Radar Cross-Section Measurements and Simulation of a Tethered Satellite

The Small Expendable Deployer System End-Mass Payload

Robin L. Cravey, Dion T. Fralick, and Erik Vedeler

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Abstract

The first Small Expendable Deployer System (SEDS-1), a tethered satellite system, was developed by the National Aeronautics and Space Administration (NASA) and launched March 29, 1993 as a secondary payload on a United States Air Force (USAF) Delta-II launch vehicle. The SEDS-1 successfully deployed an instrumented end-mass payload (EMP) on a 20-km-nonconducting tether from the second stage of the Delta II. This paper describes the effort of NASA Langley Research Center's Antenna and Microwave Research Branch to provide assistance to the SEDS Investigators Working Group (IWG) in determining EMP dynamics by analyzing the mission radar skin track data. The radar cross-section measurements taken and simulations done for this study are described and comparisons of the measured data with the simulated data for the EMP at 6 GHz are presented.

Introduction

The first Small Expendable Deployer System (SEDS-1), a tethered satellite system, was developed by the National Aeronautics and Space Administration (NASA) and launched March 29, 1993 as a secondary payload on a United States Air Force (USAF) Delta-II launch vehicle. The SEDS-1 successfully deployed an instrumented end-mass payload (EMP) from the second stage of the Delta II on a nonconducting tether 20 km long. A computer-generated image illustrating the Delta-II second stage and the EMP during the mission is shown in figure 1. The EMP instrumentation consisted of a three-axis tensiometer (i.e., load cell) at the tether attachment point, a three-axis magnetometer, a three-axis accelerometer, and a data handling and transmission system. (See ref. 1.) In addition to the onboard sensors, several ground-based radar and optical sensors supported the SEDS-1 mission. Data from the onboard and ground-based sensors are being analyzed by the SEDS Investigators Working Group (IWG). The IWG's interest in the SEDS-1 data is threefold: the performance of the expendable deployer system, the tether dynamics throughout the mission, and the rigid body dynamics of the EMP from the moment of separation from the Delta-II second stage through reentry and burnup. This paper describes the effort of the NASA Langley Research Center (LaRC) Antenna and Microwave Research Branch (AMRB) to provide assistance to the IWG in determining EMP dynamics by analyzing the mission radar skin track data. This analysis was proposed to possibly determine the EMP attitude as a function of mission time by correlating the measured and/or simulated radar cross section (RCS) as a function of aspect angle with the skin track data obtained during the SEDS-1 flight. If successful, such a correlation would permit derivation of aspect angle as a function of time based on the RCS skin track data.

To predict the RCS of the EMP at all aspect angles, an RCS simulation code was needed which was both accurate and efficient. Volumetric measurements were required to validate the code for this application. This paper documents the study and presents the comparison of the measured and simulated RCS of the EMP at 6 GHz.

Abbreviations

ACAD	advanced computer-aided design
AMRB	Antenna and Microwave Research Branch
ALCOR	ARPA-Lincoln C-Band Observable Radar
ARPA	Advanced Research Projects Agency
CW	continuous wave
EMP	end-mass payload
ETR	Experimental Test Range
GO	geometrical optics
IWG	Investigators Working Group
LaRC	Langley Research Center
NASA	National Aeronautics and Space Administration
RCS	radar cross section
RF	radio frequency
SEDS-1	Small Expendable Deployer System
USAF	United States Air Force
YIG	yttrium-iron garnet

EMP External Geometry

The EMP exterior consists of surfaces from three separate components: the fins, the cover, and the base plate as shown in figure 2. The four fins, which make up a corner reflector system, are located on the top of the EMP cover and are fabricated from 0.063-in-thick (0.160 cm) aluminum with dimensions as shown in figure 3. Each fin is located 90° from the adjacent fin. The set of four fins is mounted to the cover with a centerline offset of 45° as shown in figure 4. The cover is a rectangular box, 16 in. (40.64 cm) by 12 in. (30.48 cm) by 8 in. (20.32 cm), with an open bottom and is constructed of 0.063-in-thick aluminum. All edges and corners formed by intersecting sides are rounded. The 0.51-in-thick (1.30 cm) aluminum base plate, 16 in. by 12 in., fits within the open bottom and is attached with screws for the actual mission. The external (bottom) surface of the base plate has several cutouts as shown in figure 5. These cutouts are not through holes; a nominal 0.070-in. (0.178-cm) thickness of aluminum is left in place. The cutouts were included in the design to facilitate heating of the EMP interior during reentry to ensure complete burnup. The EMP payload adapter, shown in figure 6, is attached to the base plate to permit mounting of the payload to the launch vehicle with a clamp band release assembly (not shown). (See ref. 2.)

RCS Measurements

Three sets of RCS measurements were taken at 6 GHz for the EMP model in the LaRC Experimental Test Range (ETR). The ETR measurement system is described in detail later. A preliminary set of measurements was taken with a model assembled with the cover, corner reflector fins, and a flat bottom plate. Principal plane cut measurements were taken with the model resting on a foam column which could be rotated azimuthally through 360°. By resting the model on its bottom plate, cover long side, and cover short side, the azimuth, elevation, and roll cuts, respectively, were obtained. This set of measurements is referred to as the “simplified model measurements.” The actual bottom included numerous square cutouts and an EMP payload adapter (described in the previous section), which were of significant size in terms of wavelength. An extensive set of RCS measurements was taken with the more realistic complex model. In addition to principal plane cuts (referred to as the “complex model principal plane measurements”) for this model, a foam cradle was developed which permitted the model to be supported at various tilt angles while azimuth sweeps of 360° were performed. (See fig. 6.) The tilt angles were changed in increments of 5°. This resulted in a set of volumetric RCS data with each tilt angle corresponding to a great circle cut. This set of measurements is referred to as the “volumetric measurements.”

Scattering Range Setup

The LaRC ETR facility is a compact range designed for microwave scattering measurements in the 6- to 18-GHz frequency range. (See fig. 7.) The EMP model was placed near the center of a test zone 6 ft (1.83 m) by 8 ft (2.44 m), which provides a uniform plane wave simulating the necessary far-field conditions. A low-cross-section pylon supported the model and included a computer-controlled azimuth rotator (0° to 360°) for pattern measurements.

The ETR uses a dual reflector system. (See ref. 3.) The reflector system consists of a cosine-squared, blended, rolled-edge main reflector 16 ft (4.88 m) by 16 ft (4.88 m) and a Gregorian subreflector, which is enclosed with the feed in an anechoic dual chamber that reduces spurious radiation into the main chamber.

The ETR radar is a pulsed continuous wave (CW) system, which permits time gating to reduce background noise levels. A yttrium-iron garnet (YIG) tuned frequency synthesizer provides the radio frequency (RF) signal of 6 GHz.

System Calibration

The cross-sectional measurements are calibrated to a 6-in-dia. (15.24 cm) sphere target and are presented in dB referenced to a square meter (dBsm). The calibration procedure involved the following four-step process:

1. A 6-in-diameter (15.24-cm) calibration sphere is measured in the range.

2. The background level is measured with the sphere removed from the range. Vector subtraction is performed between the sphere and its background. An exact sphere RCS value is computed and the ratio between the exact and measured values gives a calibration factor used to convert the measured EMP values from arbitrary dB to dBsm.

3. The EMP target data is taken.

4. The EMP background data is taken. The target background includes the base of the cradle adaptor used to hold the EMP target in place for the great circle cut measurements as described previously but does not include the cradle itself. The decision not to include the upper portion of the cradle in the background subtraction was twofold. First, the EMP target was assumed to have a fairly high cross section (>-20 dBsm), which was in fact true. The foam cradles were much less than that value. Second, most of the calibration time was needed for the target (EMP) measurements as compared with the background and

reference sphere measurements. Measurements of the cradle backgrounds would have doubled the data acquisition time because new background data would need to be taken for each azimuth position.

By using this calibration technique, only two sources of error need to be characterized and reduced. First, the calibration target must be shown to be the same physical target as the computed exact target. Second, the system must be linear in dB. The calibration spheres used in this study were purchased for the purpose of calibrating microwave ranges and their certification can be obtained from the manufacturer. A linearity check can best be performed by measuring a standard target of large dynamic range. The ETR has used a 39.37-in. (1.0-m) almond test body and a 14-in. (35.56-cm) ogive for this check. Results correlated well with other measurements and computed results for similar targets at other facilities. (See refs. 4 and 5.)

RCS Simulation for EMP

Simulation Code Selection

The size of an object in terms of wavelength is an important factor in choosing a technique for numerical simulation of its radar cross section. Also of importance is the general shape of the body and those features that are expected to contribute significantly to the scattering. For example, the scattering from the corner reflectors mounted on top of the EMP cover is expected to be a significant part of the RCS at certain incidence angles; therefore, a computer code which includes multiple interactions between parts of the model (e.g., between the plates of the corner reflectors) is desirable. The size of the EMP cover at 6 GHz in terms of wavelength λ is approximately 8λ by 6λ by 4λ and of each corner reflector fin is approximately 4λ by 2λ. Unfortunately, the large size of the EMP box in terms of wavelength makes the use of an exact technique such as method of moments impractical in this case. A high-frequency technique which includes multiple interactions seems to be the best solution. The selected code and the modelling software used to obtain a computational model for the RCS simulation code are described in the next section.

Software

Computer modelling of the EMP was done with the advanced computer-aided design (ACAD) program developed by General Dynamics. The geometry information was output from ACAD in the form of a facet file, which approximates the surface as a collection of triangular patches. A conversion program was then used to create an input file for the RCS simulation software from the facet file.

The Xpatch 3.1 code, developed by the Defense Electromagnetic Analysis Company, is a high-frequency code which computes RCS for triangular flat patches with interactions. This code was used for RCS simulation of the EMP in this work. The RCS of the target is computed with a technique of shooting and bouncing rays; that is, geometrical optics (GO) rays are traced as they bounce from patch to patch. At the last bounce of each ray, a physical optics integration is done over the triangular flat patch to calculate the far field. The computation includes all GO interactions unless a first-bounce-rays-only option is specified by the user. An optional wedge diffraction contribution may also be included in the RCS computation if desired.

Results

Simplified Model Measurements and Computations

As explained in the section entitled “RCS Measurements,” the first set of EMP measurements was performed with a model assembled with the cover, corner reflectors, and a flat bottom plate. The simplified ACAD model (shown in fig. 8) was composed of a rectangular box with bevelled side and top edges and topped with four quadrilateral flat plates representing the corner reflectors. The bevelled edges were included to simulate the corner and edge radii of the test model. A facet model was created containing 92 patches and 96 wedges; Xpatch 3.1 was run for a frequency of 6 GHz for the three principal plane cuts. All ray bounces and wedge diffraction terms were included in the Xpatch 3.1 runs.

The comparisons of computed and measured data are shown in figures 9–11. As shown in the figures, good agreement was generally obtained between the computations and measurements. The most significant differences occurred in the azimuthal cut (fig. 11), where the multiple interactions from the corner reflectors have a pronounced effect.

Complex Model Principal Plane Measurements

The complex model principal plane measurements were taken on the model with the bottom plate assembled with the EMP payload adapter and other fixtures to be used in the flight experiments. (See fig. 6.) The features which were thought to be the most important for simulating the RCS of this more complicated EMP model were included in the complex ACAD model. (See fig. 12.) These include the square recesses on the bottom plate and the EMP payload adapter. The facet model for this geometry contained 1099 patches and 683 wedges, and again, all ray bounces and edge diffraction terms were used in the Xpatch 3.1 computation.

Comparisons of measured and computed data for the elevation and roll cuts are shown in figures 13 and 14. As expected, the azimuth cut data for the simplified and complex models were very similar because the bottom plate was not illuminated in this case. Similarly, the roll and elevation cut data for values of the sweep angle from 0° to 90° and from 270° to 360° are much like the simplified model data. For these angular ranges, the bottom plate was not illuminated. For the angular ranges where the bottom plate was illuminated, differences are noted between the measured and simulated data, especially in the roll cut. These differences are thought to be due to the variations between the computer model and the actual complex bottom plate. The structures on the computer model are not as detailed as on the real model; some refinement may be possible in the future if a more detailed simulation is deemed necessary for the study of the rigid body dynamics of satellites by use of RCS.

Volumetric Measurements and Computations

In figure 15, the great circle cut is shown for which the EMP model was tilted 30° about the *Z*-axis. Fairly good agreement between the measured and computed data was obtained in this case, especially for the horizontal polarization case. The angular ranges for which the bottom plate was illuminated show some discrepancies similar to those previously noted for the principal plane cuts and are believed to be due to the differences between the analytical model and the actual complex bottom plate. The differences for the other angular ranges are thought to be partially due to alignment errors. For volumetric measurements, the model (in its foam cradle) was rotated by hand with a calibrated digital inclinometer because the ETR is equipped with only an azimuth rotator. To confirm the accuracy of the model rotation, a third set of data is shown on the plots in figure 15 for an Xpatch 3.1 run in which the model was tilted 32° instead of 30° about the *Z*-axis. As can be seen, this reduced the difference between the computed and measured data. In addition, any slight deviation of an electrically large flat plate from vertical can cause a large deviation in the measured results and is another possible source of measurement error.

Flight RCS Data

Figure 16 shows a plot of the RCS narrow band data obtained by the Advanced Research Projects Agency ARPA-Lincoln C-Band Observable Radar (ALCOR) at Kwajalein Atoll. (See ref. 6.) Before a comparison is made between the ALCOR data and ETR measured data, note that the ALCOR data is circularly polarized, and the two traces shown on the plot give prime and orthogonal polarizations. The measured data from ETR is linear copolarized data because of measurement constraints within the facility. This makes direct comparison between the two data sets difficult. Also, note that the ALCOR radar operates at a C-band frequency of 5.664 GHz, which is slightly lower than the minimum frequency of 6 GHz in the ETR. The frequency difference is not considered significant enough to affect the conclusions reached in the paper. Despite the differences in frequency and polarization between the data sets, some general trends can be noted. The ALCOR data have a maximum value of about 18 dBsm, which is also approximately the maximum value obtained by the ETR measurements and the simulations. Finally, most of the RCS values for the ALCOR data tend to lie in the ±10-dBsm range, which is also true for the ETR and simulated data.

Conclusions

Because of the number of degrees of freedom in the orientation of the EMP at any time during its visibility and the type of RCS data which was obtained during the mission, inference of orientation with any degree of certainty from correlating the sets of data does not seem feasible. In particular, at any given RCS value between ±10 dBsm, a large number of possible orientations exist. To uniquely associate an orientation with an RCS value from the mission skin track data appears to be a very time-consuming task and may not be possible with present instruments. The task is further complicated in this case when considering the polarization difference between the ALCOR data and ETR measurements. Although circularly polarized data could be simulated with the Xpatch 3.1 code, the cross-polarized simulation data could not be validated by measurements because of the measurement constraints within the facility.

This study does illustrate the usefulness of the Xpatch 3.1 code for predicting the RCS of a moderately complex three-dimensional geometry. This conclusion is supported by the high degree of agreement between the predicted RCS data of Xpatch 3.1 and the measured RCS data of the EMP at 6 GHz.

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November 16, 1994

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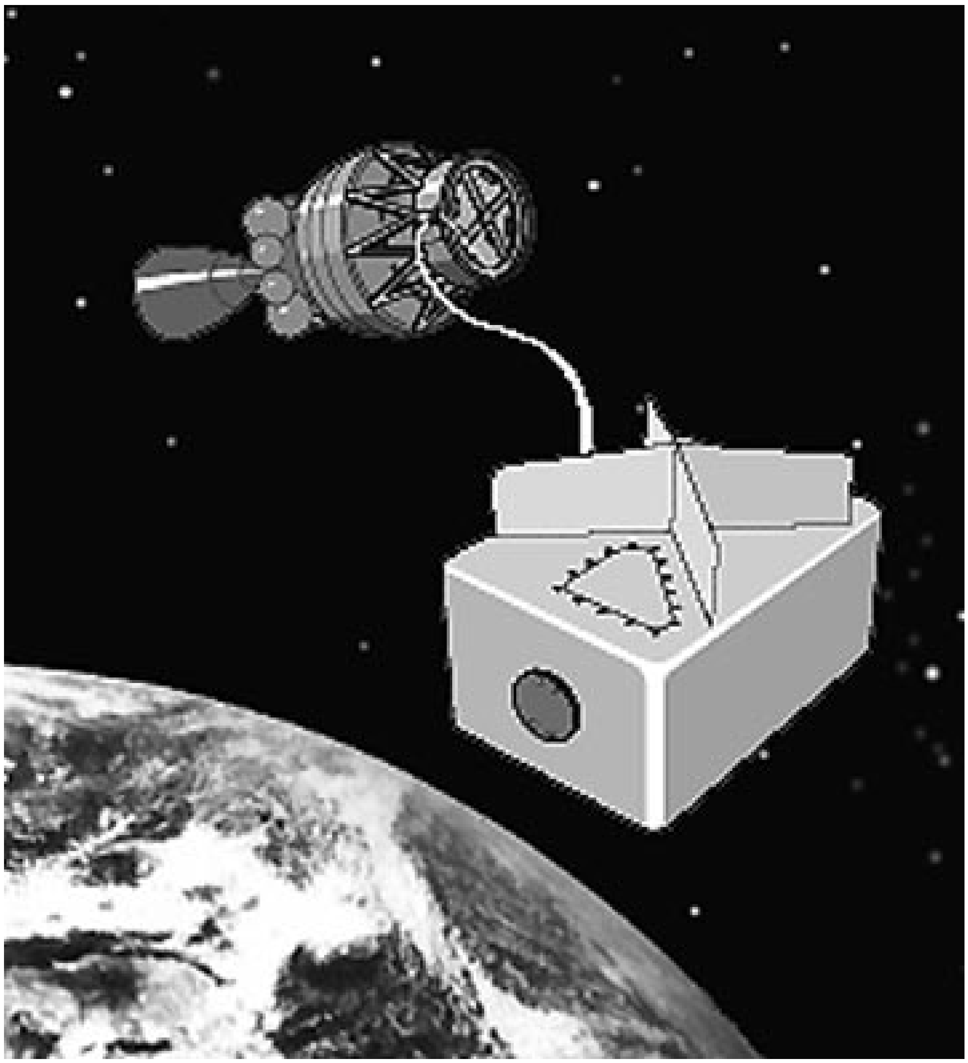

Figure 1. Delta-II second stage and EMP.

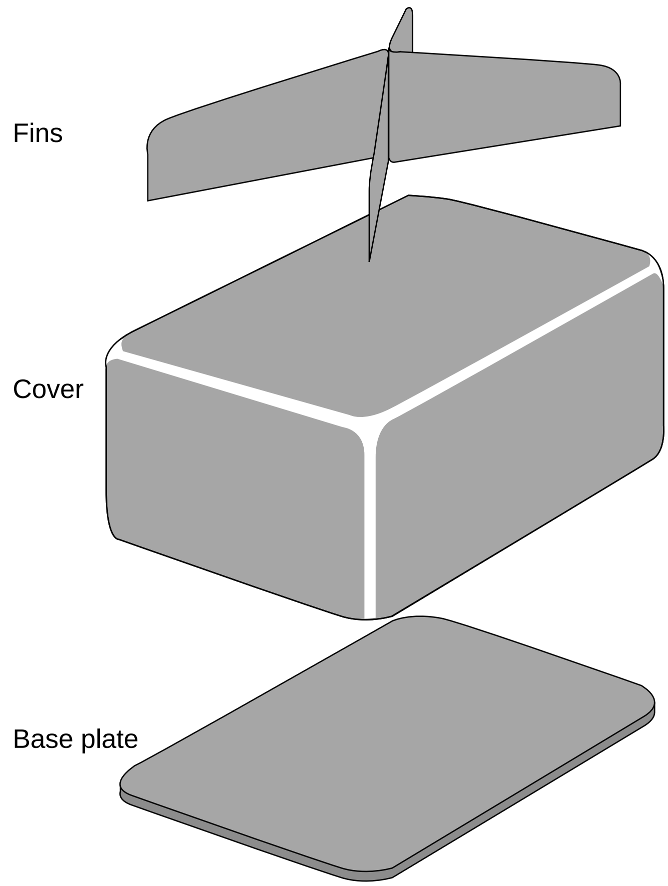

Figure 2. Basic elements of EMP model.

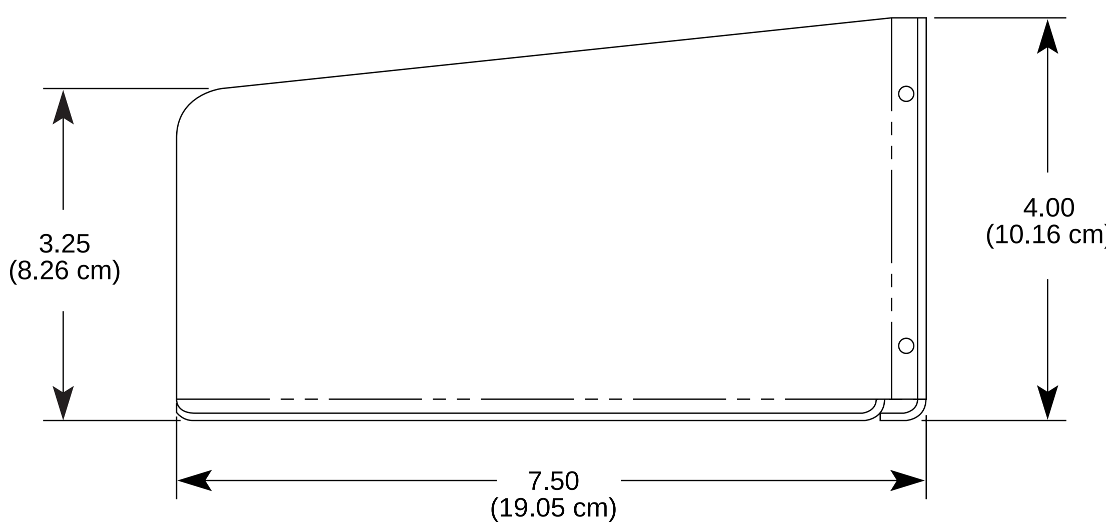

Figure 3. Fin dimensions. All linear dimensions in inches except as noted.

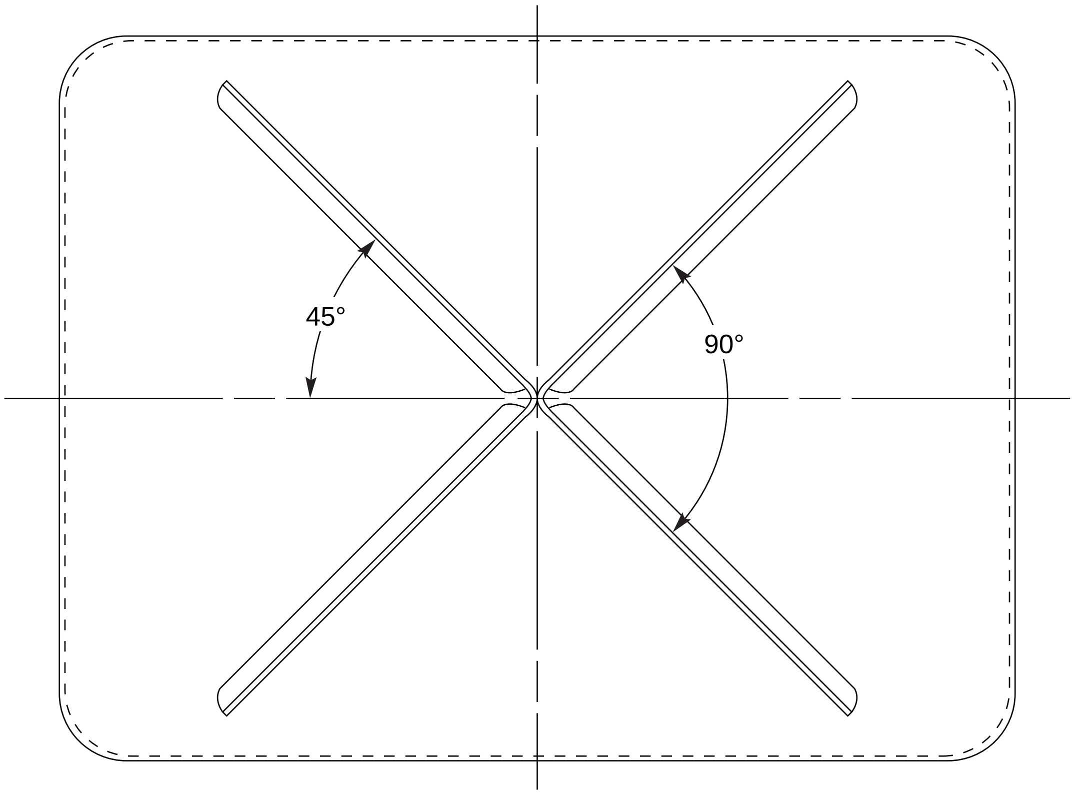

Figure 4. Fin geometry.

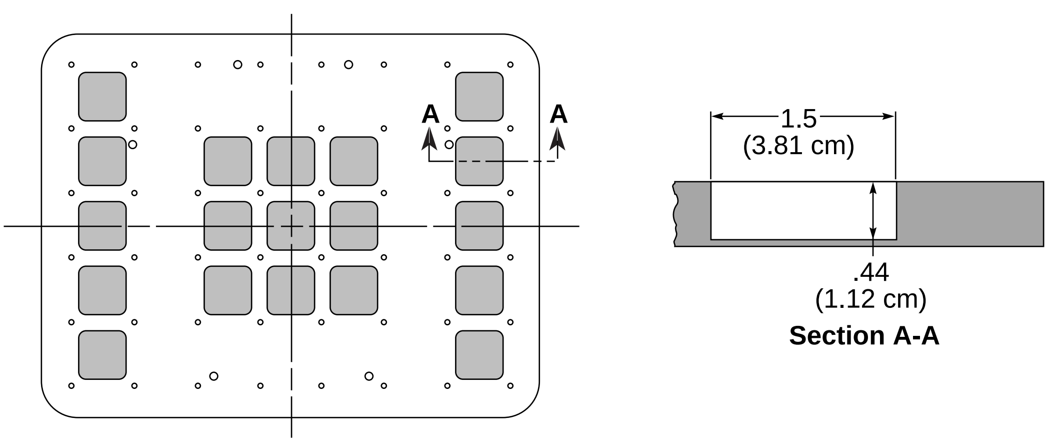

Figure 5. Bottom plate cutouts. All linear dimensions in inches except as noted.

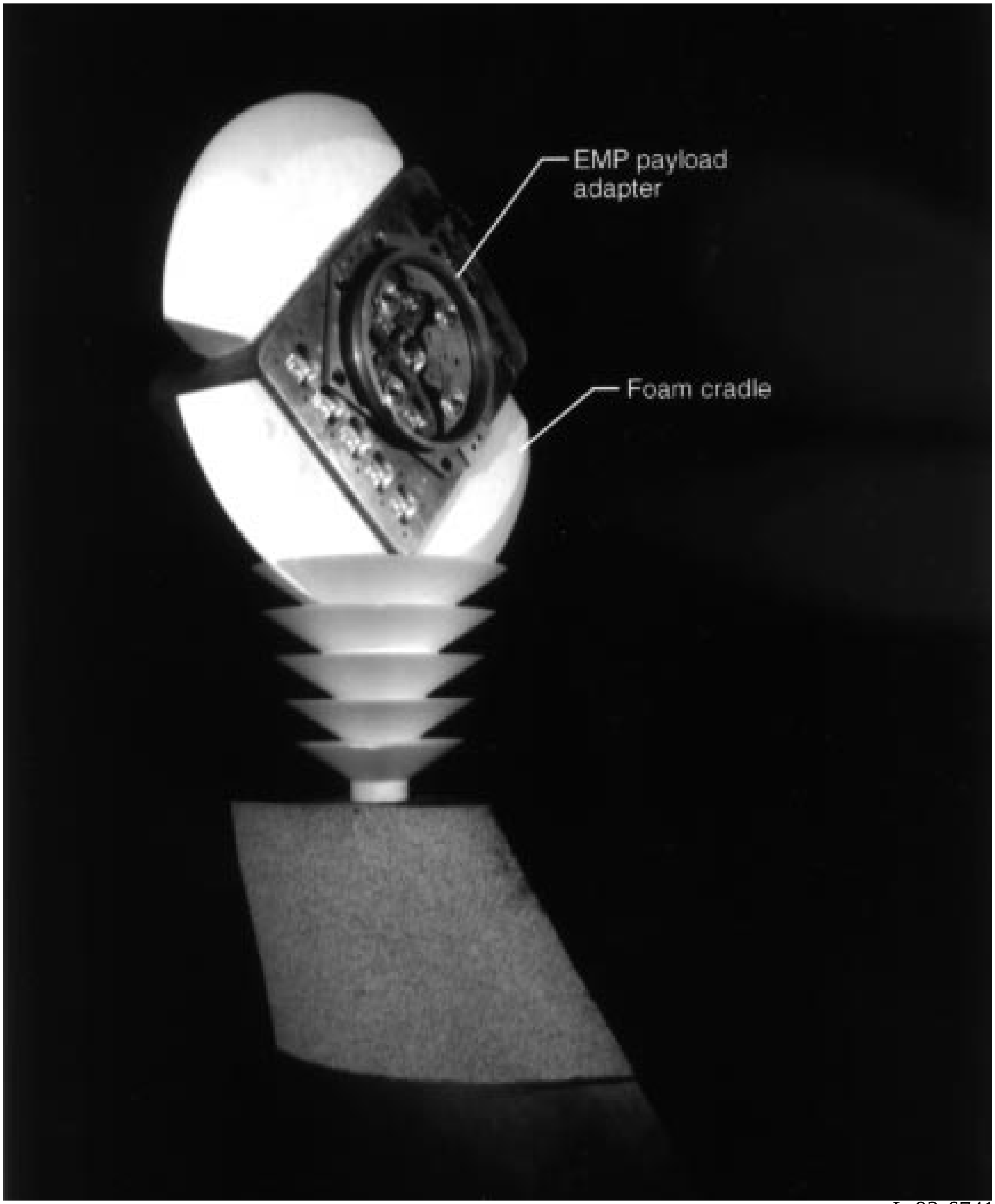

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Figure 6. EMP model in foam cradle.

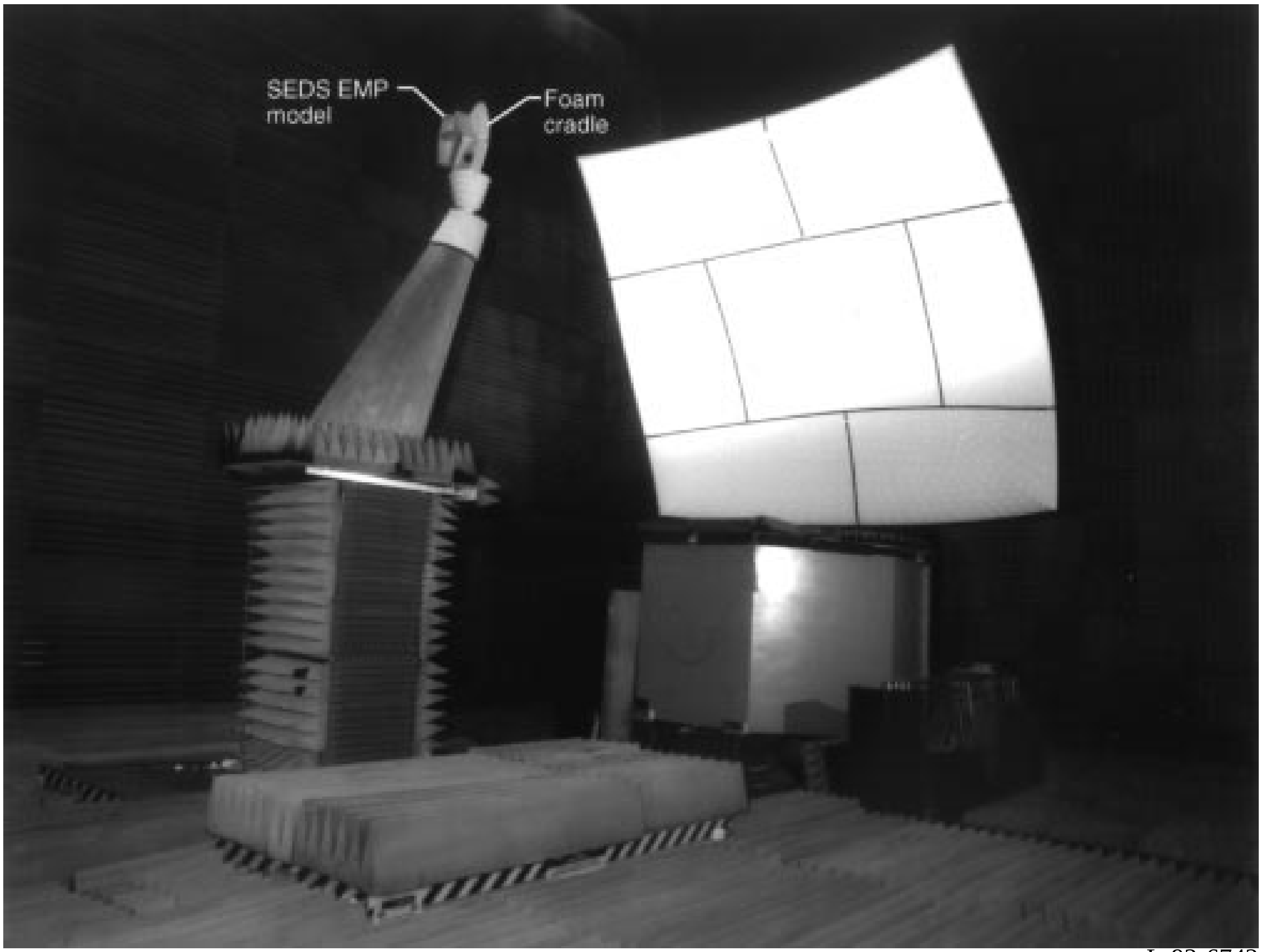

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Figure 7. EMP model in ETR facility.

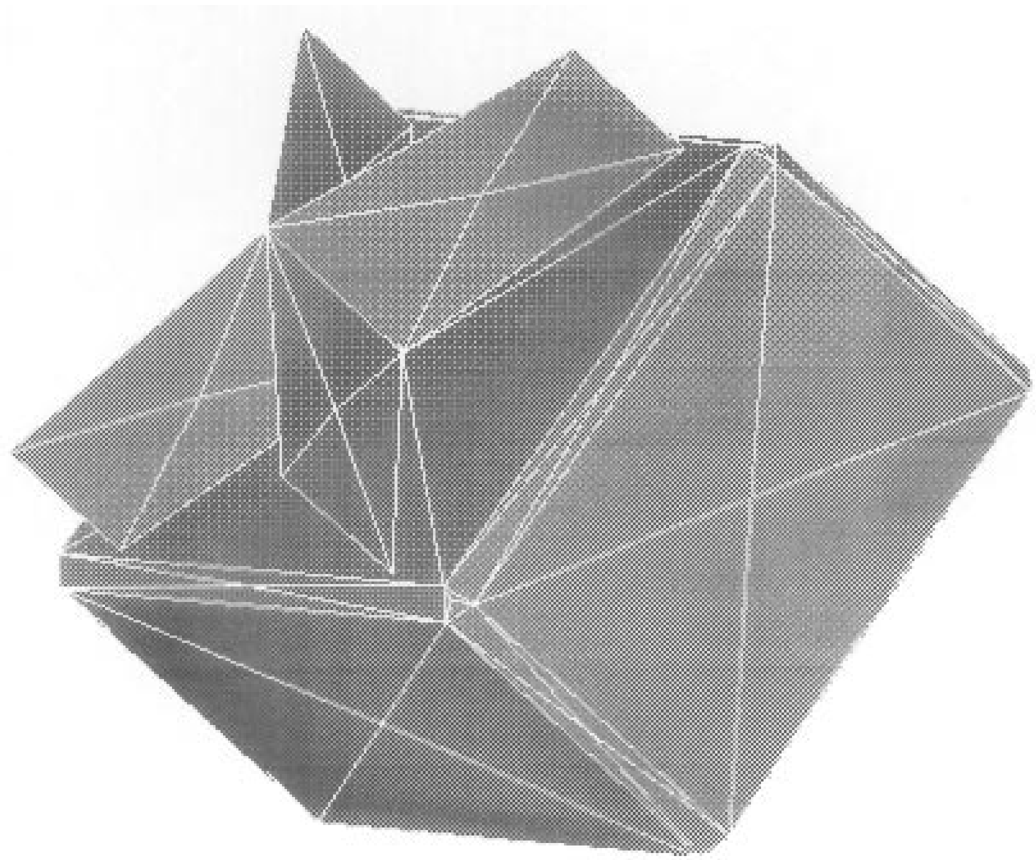
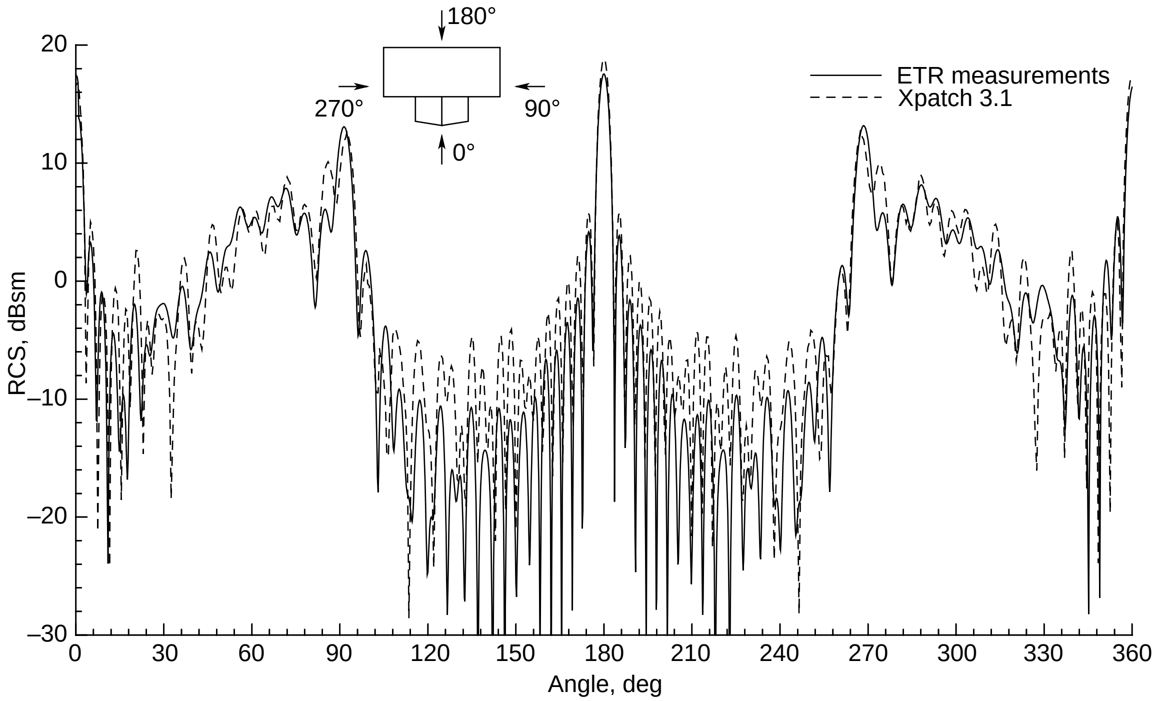
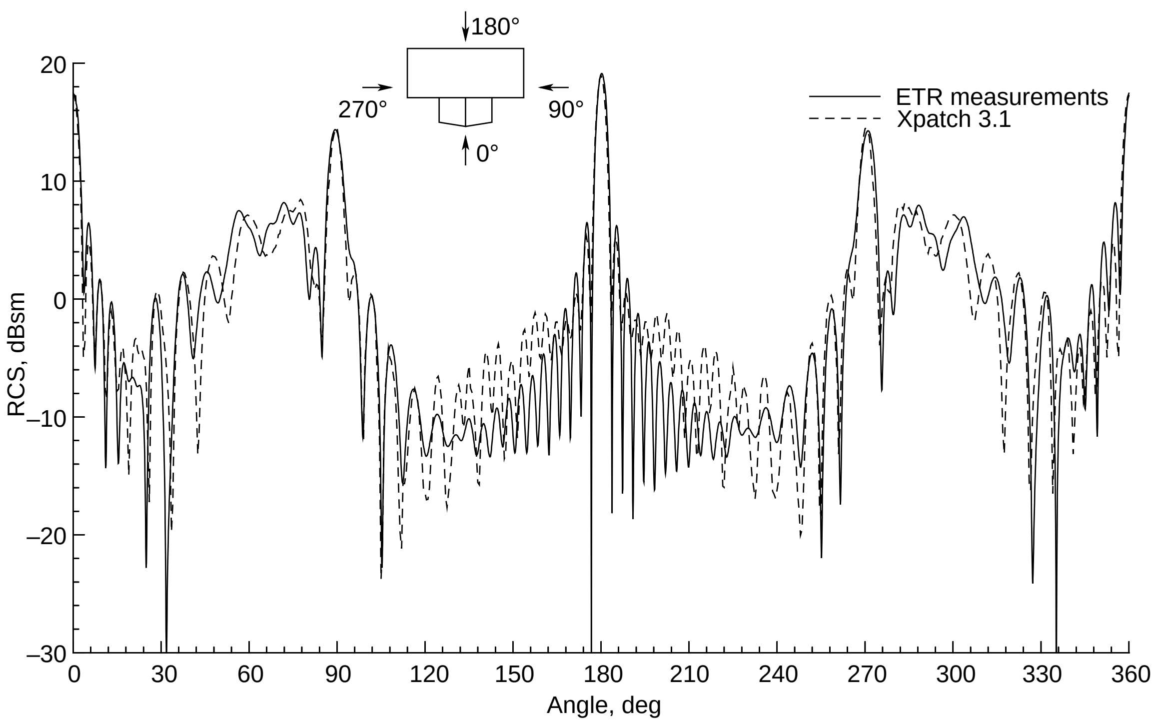


Figure 8. Simplified ACAD model.

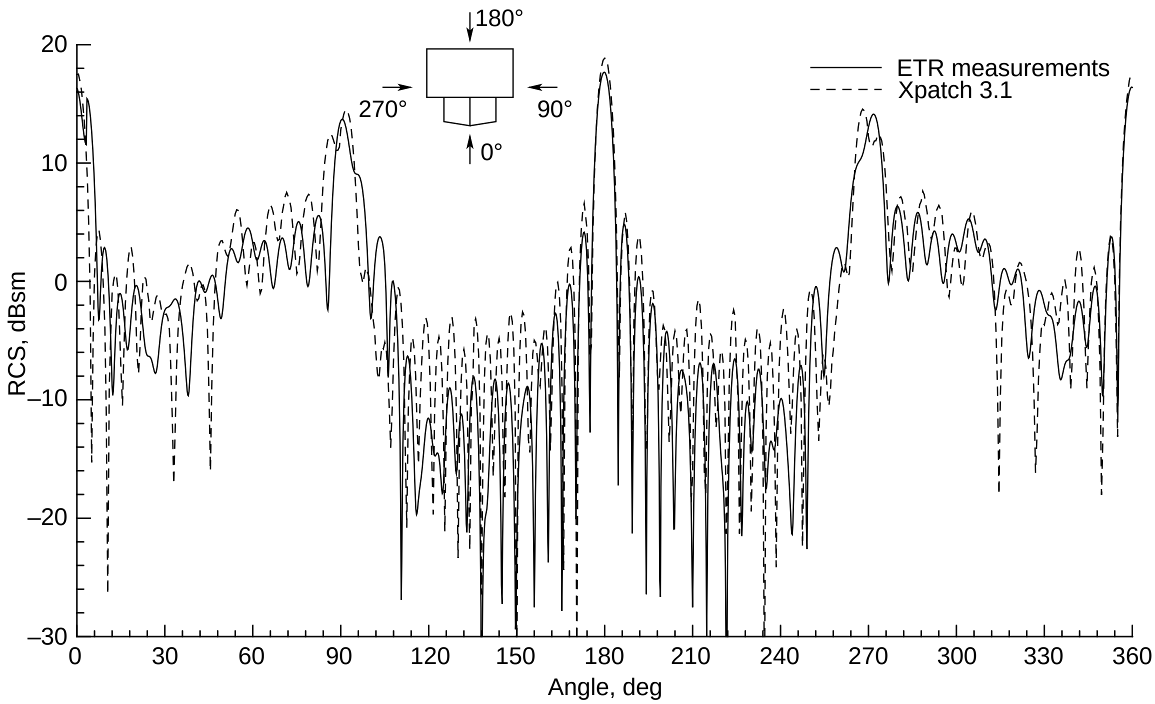


(a) Horizontal polarization.

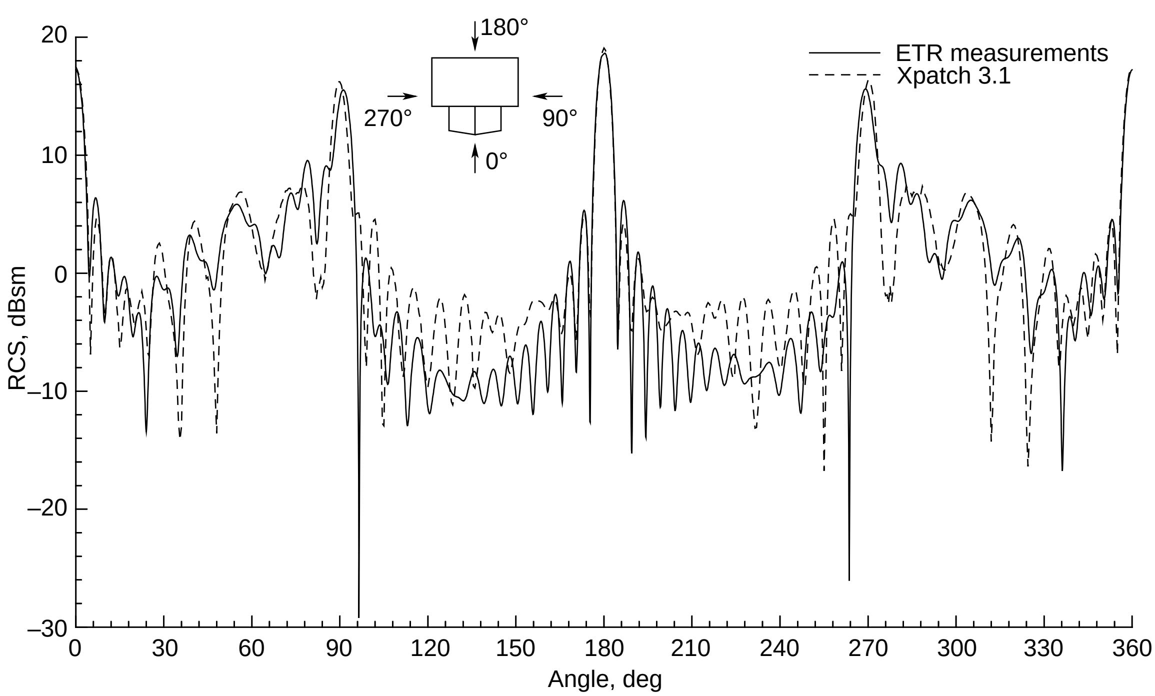


(b) Vertical polarization.

Figure 9. Simplified model principal plane elevation cut.

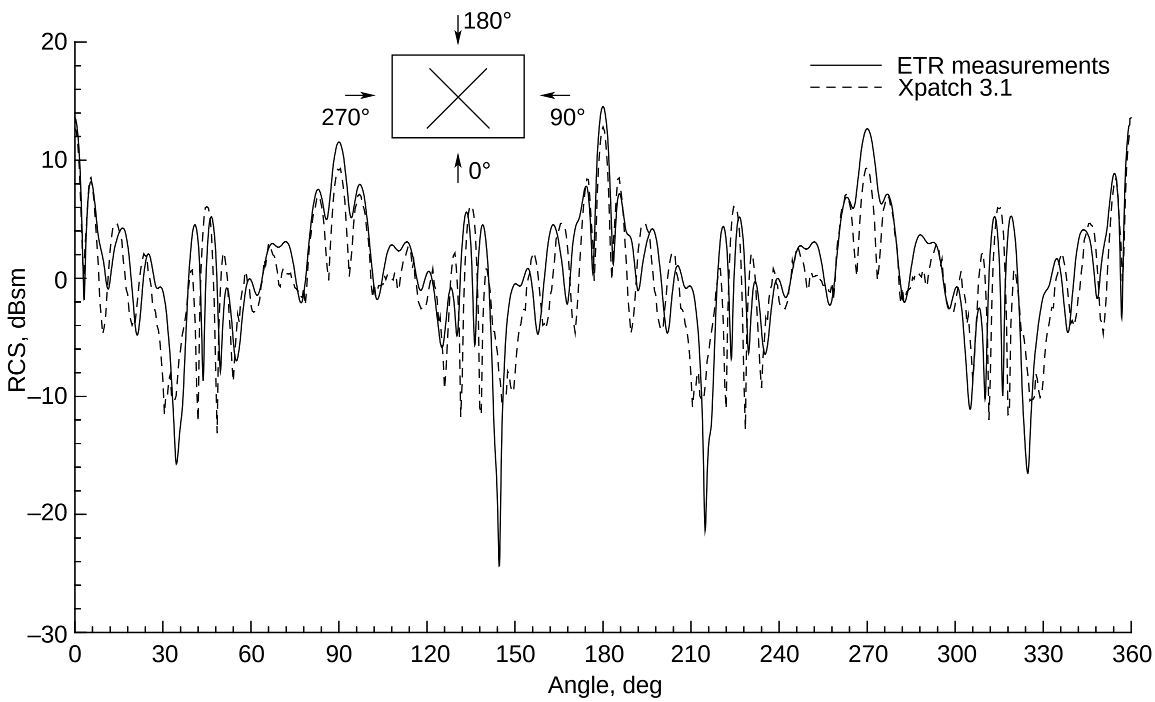


(a) Horizontal polarization.

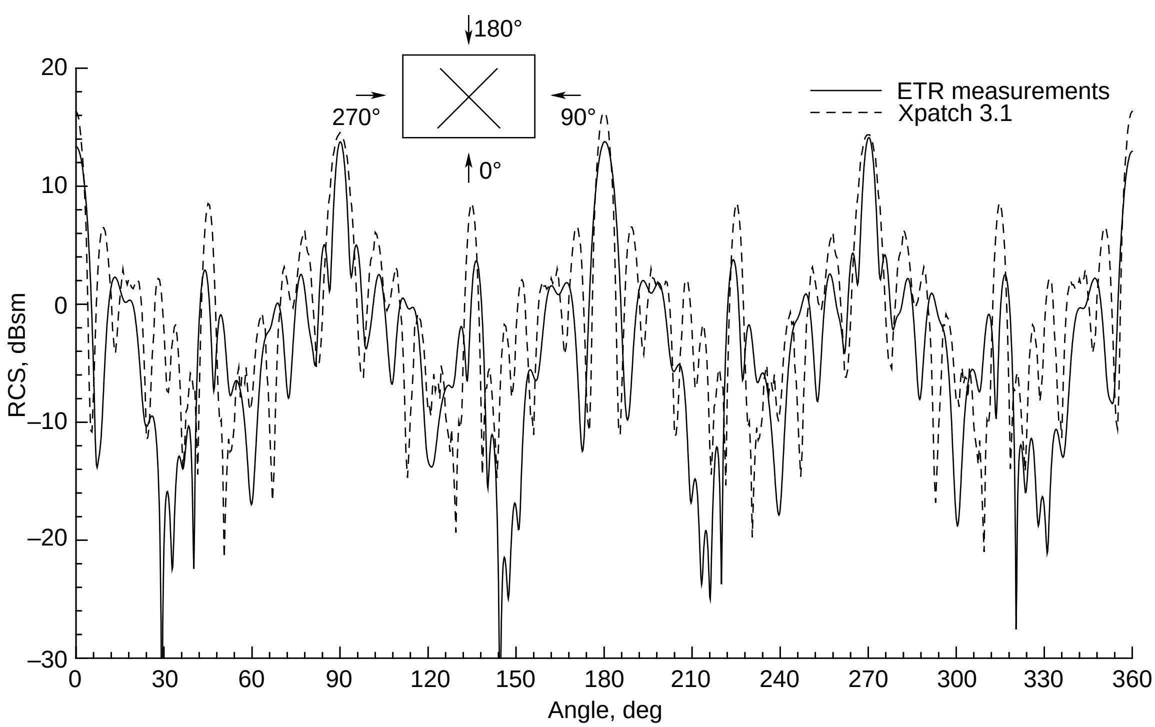


(b) Vertical polarization.

Figure 10. Simplified model principal plane roll cut.



(a) Horizontal polarization.



(b) Vertical polarization.

Figure 11. Simplified model principal plane azimuth cut.

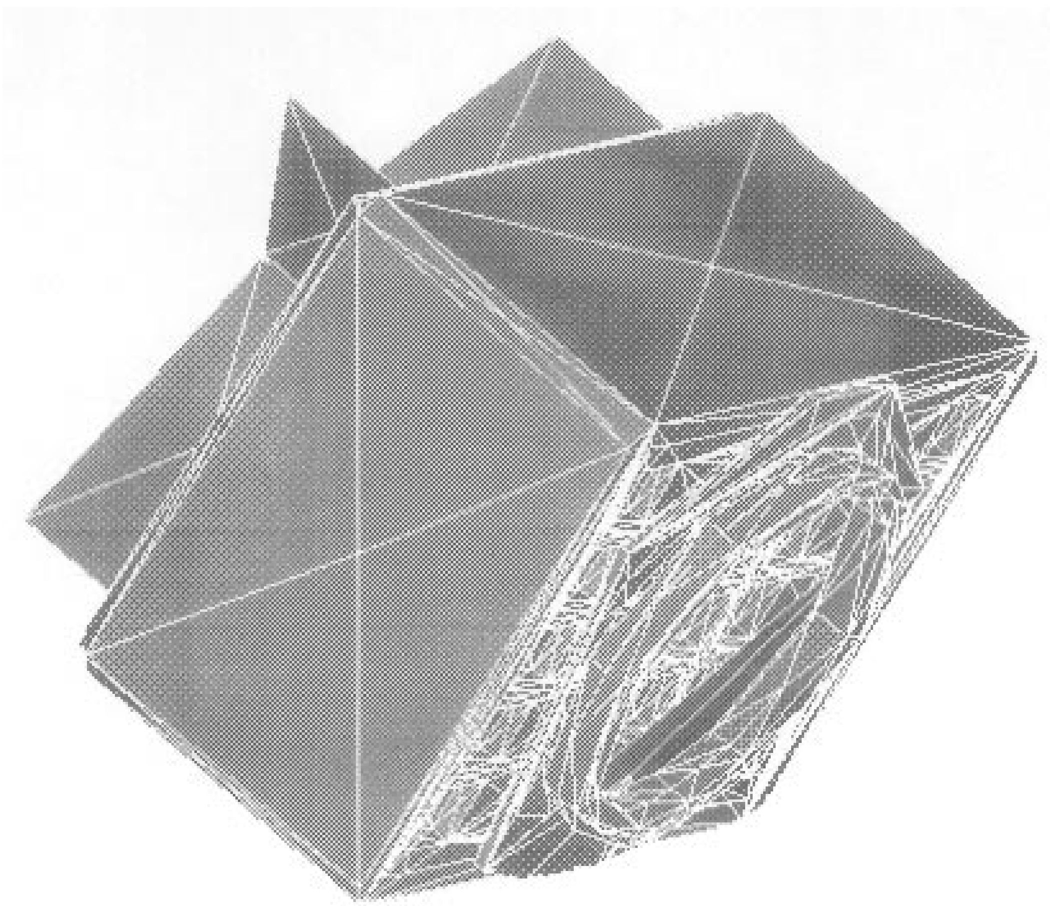
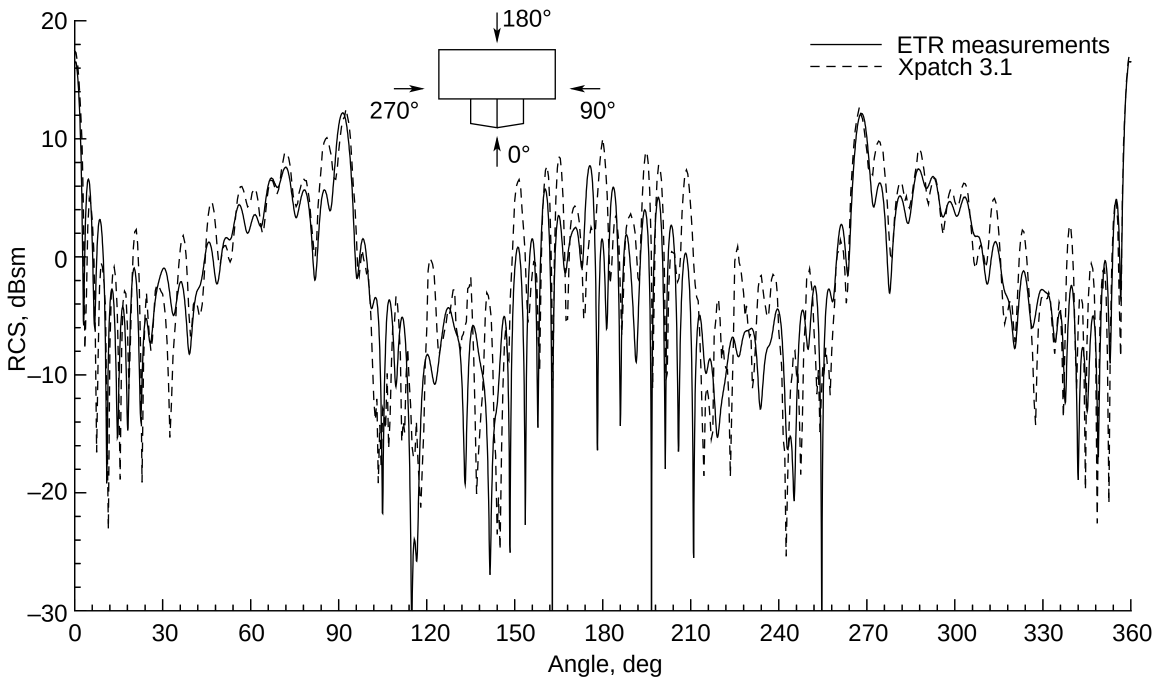
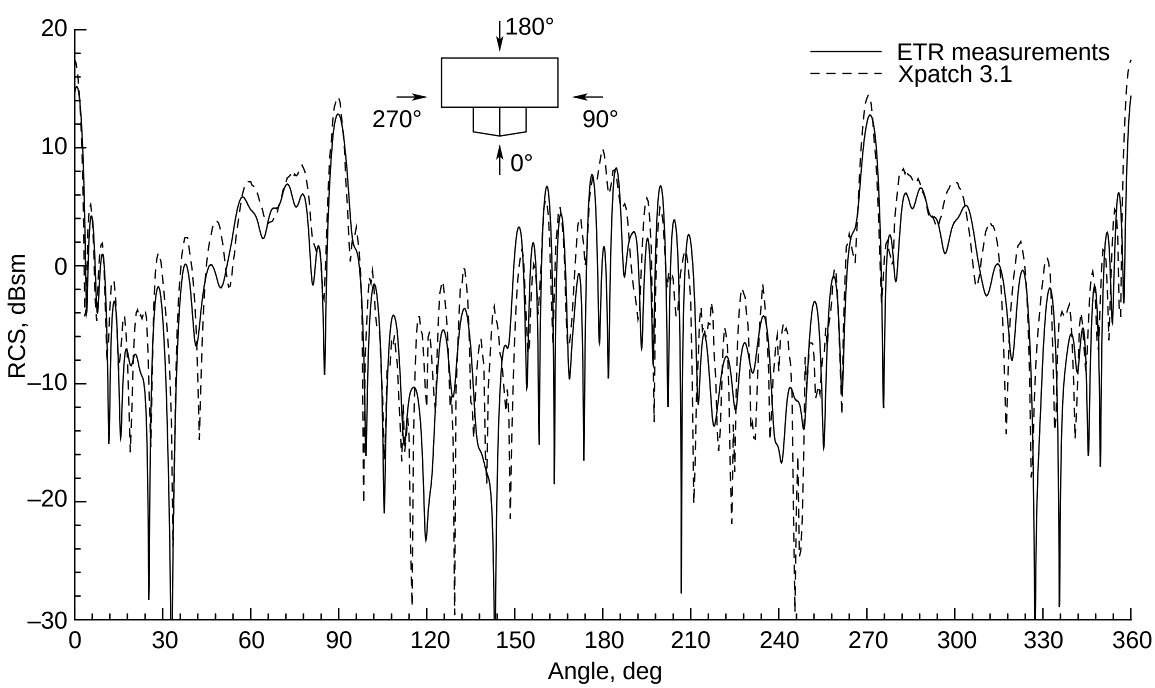


Figure 12. Complex ACAD model.

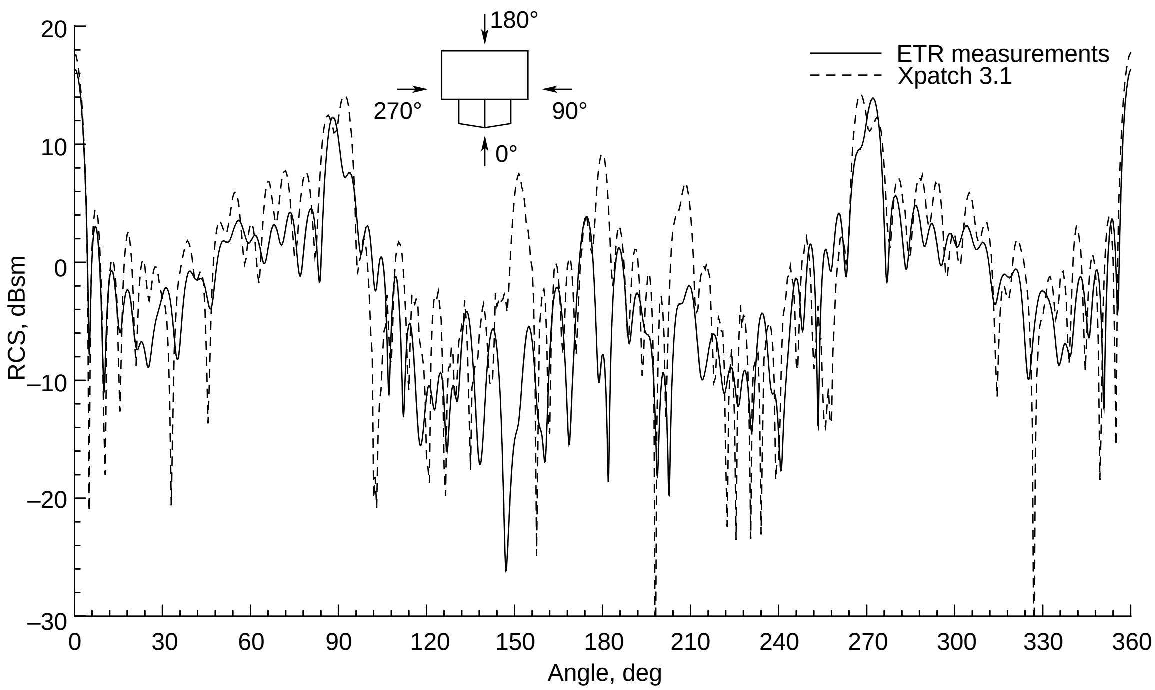


(a) Horizontal polarization.

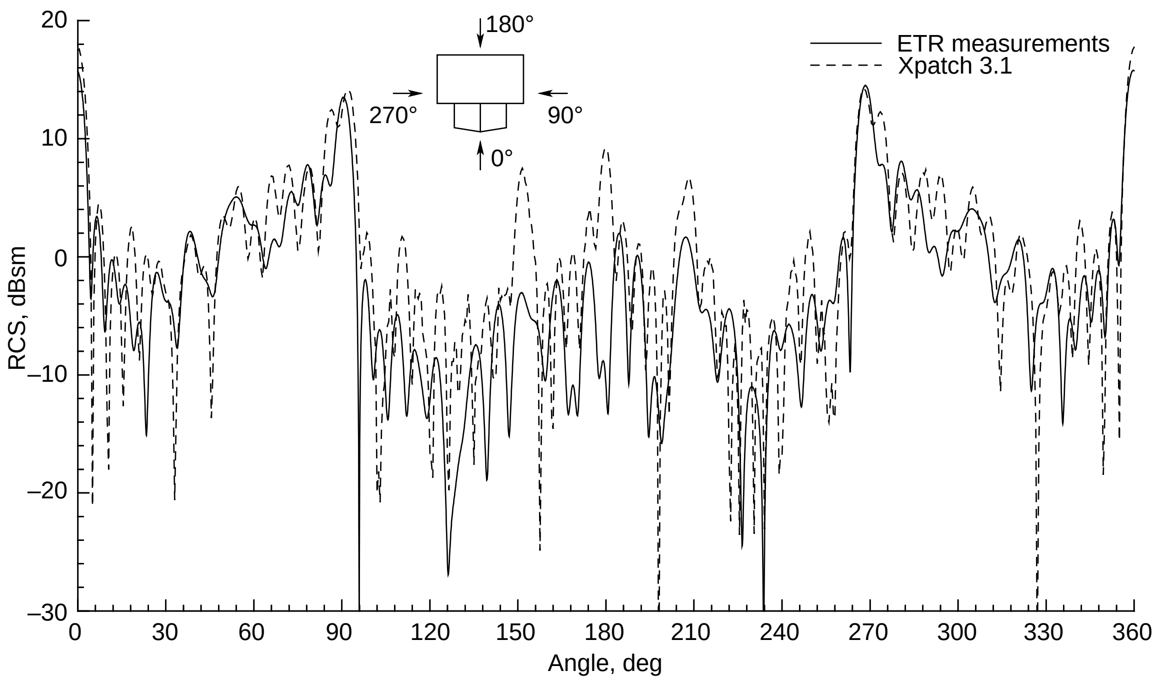


(b) Vertical polarization.

Figure 13. Complex model principal plane elevation cut.

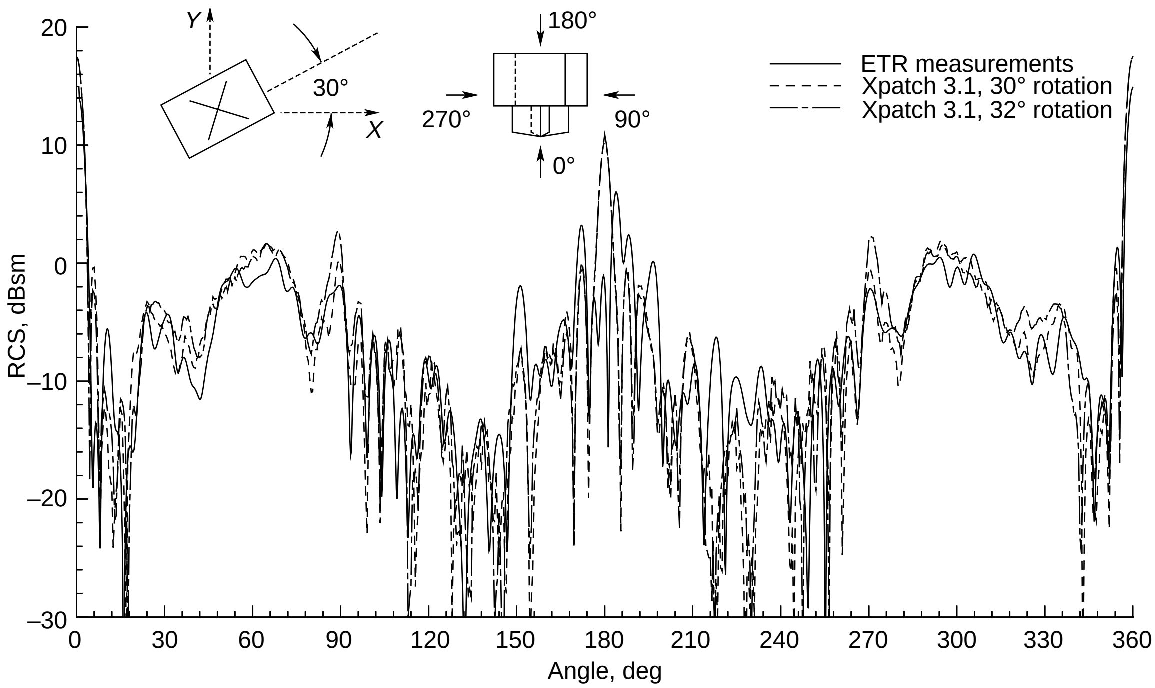


(a) Horizontal polarization.

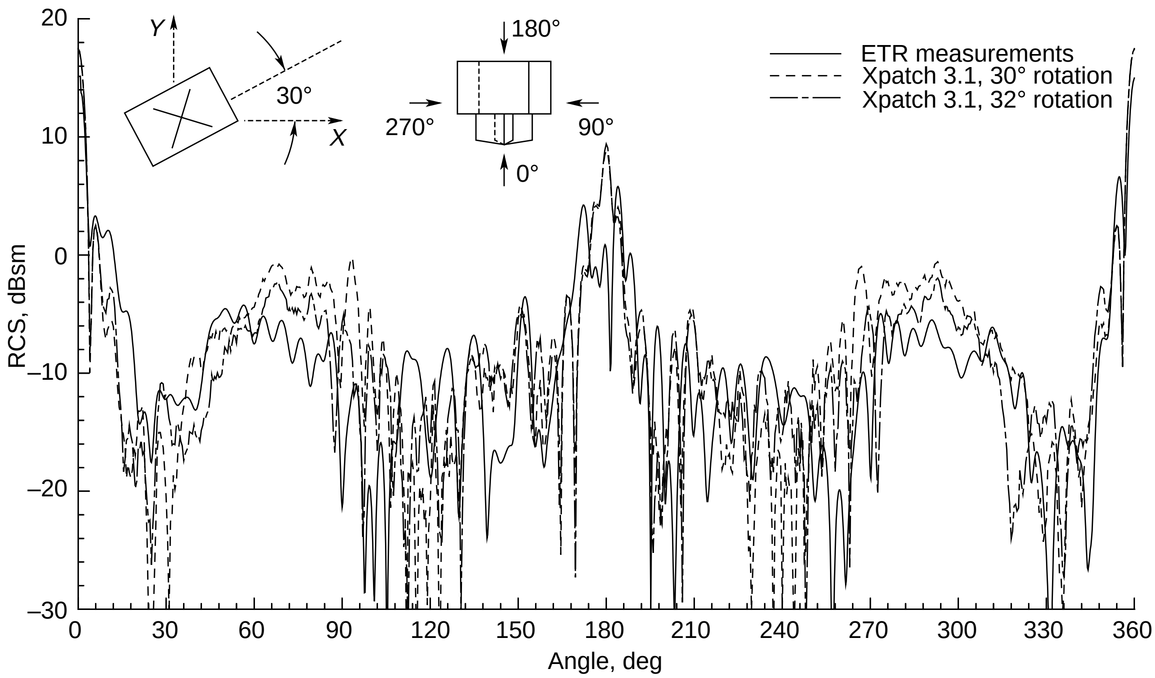


(b) Vertical polarization.

Figure 14. Complex model principal plane roll cut.



(a) Horizontal polarization.



(b) Vertical polarization.

Figure 15. Complex model great circle cut; tilt = 30°..

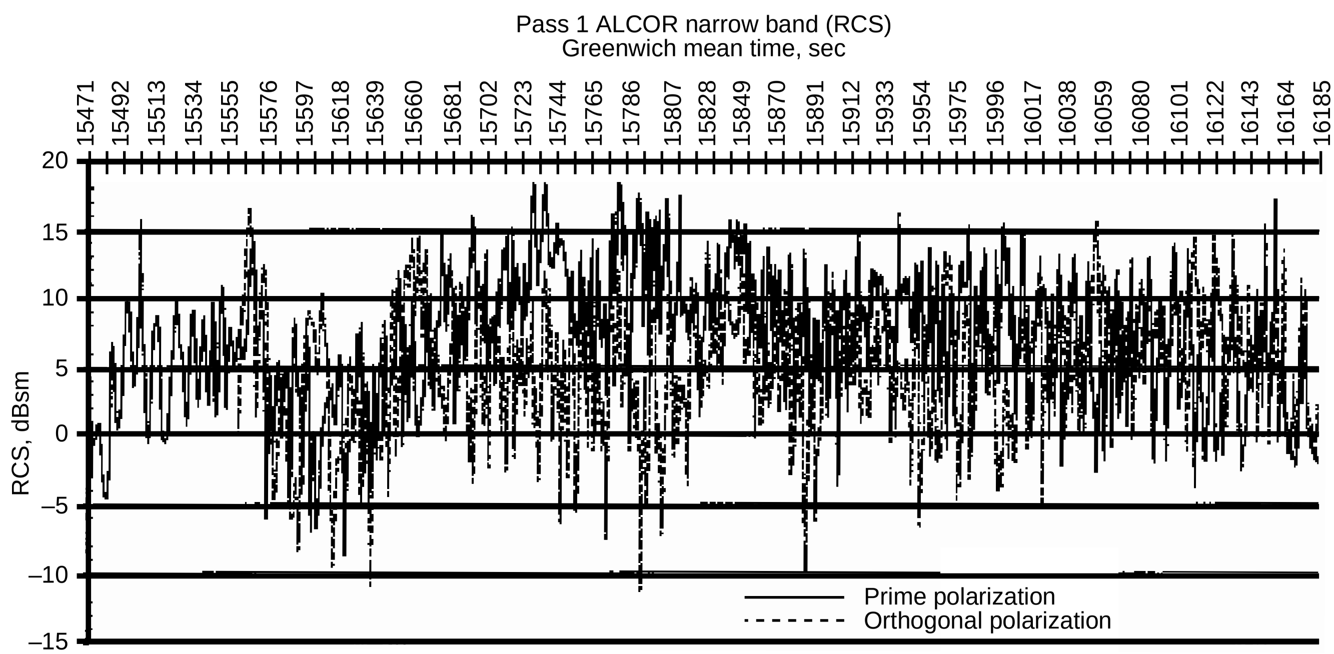


Figure 16. ALCOR narrow band RCS data.

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13. ABSTRACT *(Maximum 200 words)*
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